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Bolko von Rodern
National Center for Photovoltaics
National Renewable Energy Laboratory
1617 Cole Boulevard
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RE: Quarterly Report VI (May - July 2006)
"Characterization and Analysis of CIS and CdTe Cells"
Subcontract XXL-5-44205-03

For additional information: www.physics.colostate.edu/groups/photovoltaic

Dear Bolko,

PhD Completion. During the past quarter, both Samuel Demtsu and Caroline Corwine completed their PhD degrees. The two theses, Samuel's "Impact of Back-Contact Materials on Performance and Stability of CdS/CdTe Solar Cells" and Caroline's "Role of the Cu-O Defect in CdTe Solar Cells," are on the webpage above. In both cases, much of the experimental work was done at NREL, and we are especially grateful to Dave Albin, Tim Gessert, and Pat Dippo for their collaboration and mentoring. Samuel has now joined SoloPower to work on CIGS cells, and Caroline is in discussions with two small companies.

CdTe Voltage Limitations. We refined our preliminary work on CdTe voltage limitations, the primary issue for higher efficiencies, that was presented at the CdTe team meeting earlier in the year. The first question was why there is a 230-mV difference between the best CdTe voltages and the best GaAs when adjusted for band-gap difference, whereas the comparable difference between CIGS is only about 30 mV. The second question is how and whether this voltage difference can be significantly reduced without creating other difficulties. Success would translate into efficiencies above 20%.

The answer to the first question is that current CdTe cells have a combination of low carrier density (~10^{14} cm^{-3}) and low absorber lifetime (generally below 1 ns).

In some cases, the voltage is further compromised by the presence of a significant back-contact barrier. What numerical simulation has shown is that even large increases in lifetime alone will have only a minor impact on voltage. There would need to be a concurrent increase in carrier density to roughly the 10^{17} range to approach GaAs voltages.

Since both lifetime and carrier density are likely limited by extraneous band-gap states (lifetime by excessive recombination and density by excessive compensation), successful strategies to reduce these states could increase both lifetime and carrier density. At that point, however, an additional problem may arise. The unfavorable cliff-like offset between CdS and CdTe is a minor issue if voltage is severely limited for other reasons, but if the other problems are solved, interfacial recombination will likely become the voltage-limiting factor.

An alternative approach to increasing lifetime and carrier density (basically making CdTe into GaAs) is to form a p-i-n structure with a back electron-reflection barrier. That barrier height would need to be a modest-sounding 0.2 eV, or greater, but to date the CdTe back-contact has always had a barrier to holes of 0.3 eV or more in the opposite direction. It may be possible to form an electron barrier with a higher band-gap material such as ZnTe at the back, but the interface between CdTe and that material must be very good or its purpose of the barrier is defeated.

I presented the work on CdTe voltage in an invited talk, “Strategies to increase CdTe solar-cell voltage,” at the E-MRS meeting in June. The manuscript, co-authored by Jun Pan, has been accepted by Thin Solid Films. A related earlier paper, “Hole-current impedance and electron-current enhancement by back-contact barriers in CdTe thin-film solar cells” by J. Pan, M. Gloeckler, and J.R. Sites has now been accepted for publication in the Journal of Applied Physics. It explains how different combinations of CdTe lifetime and back-barrier height lead to features commonly seen in the J-V curves of CdTe cells.

Role of Copper in CdTe Cells. In Samuel Demtsu’s thesis work, done in collaboration with Dave Albin at NREL, he showed that an optimal amount of Cu will increase the hole density of the CdTe by forming deep acceptor states, but that Cu also forms mid-gap defect levels that act as recombination centers. Thus, Cu may increase of decrease the carrier density depending on the details. The mid-gap states, however, will lower the lifetime, and consequently reduce V_{oc} and FF. Samuel also showed that the presence of Cu in the CdS layer can have a major effect on the dark J-V curve and hence lead to dark/light crossover and to apparent quantum efficiencies larger than unity. Under operating conditions (one-sun illumination), however, photoconductivity of the CdS very nearly eliminates the impact of Cu in the CdS on cell performance.

Previous experience at NREL had indicated that graphite-paste contacts need to be annealed at 280°C. Samuel determined, however, that when the Cu contacts were evaporated, a lower anneal temperature of approximately 200°C is sufficient. Cu in elemental form may be more mobile, relative to Cu incorporated as $Cu_{1.4}Te$ in the standard NREL graphite-paste contacts. Samuel presented both the effects of copper on the CdTe absorber and the evaporated-copper work at the 4th World Conference in Hawaii. The manuscript, co-authored by Dave Albin and myself is entitled, "Role of copper in the performance of CdS/CdTe solar cells."

Thin CIGS Absorbers. Our earlier numerical simulations showed, under a variety of assumptions, including an effective back electron reflector, that progressive, uniform thinning of CIGS absorbers leads to lower values for all three J-V parameters, but there should not be a critical thickness at which there is a dramatic decrease. Since then we also explored back illumination of thin absorbers, and more lately, what can be expected when thin absorbers are not uniform.

Ana Kanevce's conclusion about front and back illumination is that the two responses will converge somewhat below 0.5 micron, as one would intuitively expect. Her uniformity work on thin CIGS is in progress, following earlier work by Uwe Rau, and also Victor Karpov's work on weak-diode regions in CdTe. She is looking at both variations in thickness and in band gap. Both of these basically reduce to the weak diode problem where the key parameters are the variations in local voltage and the sheet resistance of the TCO. Again, the preliminary results are as expected intuitively: the impact of non-uniformity is larger for thinner absorbers.

Other Activities. I attended the European-based SOLARPACT discussions following the E-MRS meeting in June and gave a presentation on the variations seen in CdTe J-V curves from different laboratories. I also participated in the Defect Workshop in Frejus also following E-MRS. In my workshop presentation, I repeated our arguments of why the CIGS grain boundaries must be relatively benign to produce the voltages seen with CIGS cells, and I described why a band-gap expansion in the valence-band direction near a grain boundary is likely necessary for the benign grain boundaries.

The results of our joint project with Prof. Marko Topic of the University of Ljubljana in Slovenia to determine the effective efficiency of photovoltaic modules from different companies based on the measured annual distribution of field conditions have been published in Progress in Photovoltaics. Additionally, I presented a poster on the straightforward procedure we developed for determining effective efficiency at the World PV Conference in Hawaii, and Marko will present a refined annual-summation procedure at the European meeting in September.

We have also worked closely with HelioVolt Corporation to help it develop its J-V and QE characterization facility. Tim Nagle spent ten days on-site there, and the result is a facility that now produces J-V and QE results very similar to those measured at NREL for the same cells. Back home, Tim has written interactive QE-analysis software analogous to Markus Gloeckler's CurVA software for J-V analysis. In a second collaborative project, Ana Kanevce worked with Raghu Bhattacharya to characterize and analyze his recent high-efficiency CdZnS/CIGS cells.

With our QE measurement system, Alan Davies and undergraduate-student Jacob vander Vliet have done a complete recalibration and major upgrade of the measurement software and procedures. Additionally, Alan has designed an LED light-bias system for both white and red light, and I should be able to report on its implementation next quarter. Finally, a new graduate student, Galym Koishiyev has redone the Labview software we use to operate our capacitance-voltage measurement system.

Sincerely,

James R. Sites
Professor

Cc: Ken Zweibel
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